

**MAGNETORESISTIVE SENSOR WITH DECOUPLED HARD BIAS
MULTILAYERS**

5 FIELD OF THE INVENTION

 This invention relates to magnetic sensors for disk drives, and more particularly to magnetic biasing of a free layer of a magnetic sensor.

10 BACKGROUND

 Thin film magnetoresistive sensors or heads have been used in magnetic storage devices (e.g., disk drives) for several years. Such a sensor includes a layer of magnetoresistive material which is conventionally referred
15 to as the free layer. The electrical resistivity of the free layer changes in response to an external magnetic field. Thus, magnetically recorded information is detected by sensing electrical resistivity changes in the free layer.

20 The free layer is typically a ferromagnetic material having a low coercivity, such as a NiFe, CoFe or NiCoFe alloy, so that its magnetization (also referred to as magnetic moment) can change easily in response to changes in the external magnetic field being sensed. In addition,
25 it is highly desirable that the free layer be in a single magnetic domain state. If multiple magnetic domains, or vortex domain states, are present within the free layer, sensor performance will be degraded due to Barkhausen jumps and other undesirable magnetic domain motion and
30 reorientation phenomena induced by the external magnetic fields to be sensed.

In order to ensure the free layer remains in a single magnetic domain state, a magnetic bias for the free layer is typically provided by bias structures adjacent to the free layer. These bias structures are usually made of hard
5 (i.e., high coercivity and high magnetic moment) ferromagnetic materials, such as CoPt, and CoCrX alloys. Here X can be Pt, Ta, Ni or other elements.

Figure 1 shows a typical bias configuration for a magnetic sensor free layer. A free layer **10** is biased by
10 bias layers **12** and **14**. Magnetizations **18** and **20** of bias layers **12** and **14** are typically set by application of a biasing magnetic field to the entire structure including layers **10**, **12**, and **14** at a relatively late stage of assembly. The biasing magnetic field has a field strength
15 exceeding the coercivity of bias layers **12** and **14**, so that when the biasing magnetic field is removed, remanent magnetizations **18** and **20** in bias layers **12** and **14** remain. Thus bias layers **12** and **14** act as permanent magnets for biasing free layer **10**.

20 Magnetizations **18** and **20** of bias layers **12** and **14** induce a magnetization **16** in free layer **10**. Magnetization **16** can be induced in free layer **10** by the process of magnetic exchange coupling, if free layer **10** is in direct contact with bias layers **12** and **14** (as shown on **Figure 1**).
25 Alternatively, magnetization **16** can be induced in free layer **10** by the process of magnetostatic coupling, if free layer **10** is not in direct contact with bias layers **12** and **14**. Magnetization **16** should be large enough to ensure that free layer **10** remains in a single-domain state. However,
30 magnetic sensor sensitivity decreases as the magnetic bias increases, so magnetization **16** is typically chosen to

provide a suitable margin over the minimum required to force free layer **10** into a single-domain state.

In operation, an electrical current (not shown on **Figure 1**) is typically passed through free layer **10** in the Y direction on **Figure 1**, so that changes in resistivity of free layer **10** can be monitored. Therefore, magnetization **16** is frequently referred to as a longitudinal magnetization because it is in the same direction as this electric current.

Since magnetization is a vector quantity, having both a magnitude and a direction, magnetizations **16**, **18**, and **20** are to be understood as Y-components of the magnetizations in the corresponding regions (i.e., **10**, **12** and **14** respectively). In practice, it is typically not possible to completely control magnetization direction, and the resulting variability tends to have a significant effect on performance.

Figure 1 shows a view of layers **10**, **12**, and **14** as seen looking up from a magnetic recording disk (i.e., the disk is in the X-Y plane of **Figure 1**). Furthermore, a track on the disk moves in the X direction on **Figure 1** as the disk rotates. Since the X extent of free layer **10** largely determines the density of information that can be read from the track, reduction of the X extent of free layer **10** is a primary goal as disk drive technology evolves. The other dimensions of free layer **10**, and the dimensions of bias layers **12** and **14** also tend to decrease as disk drive technology evolves. For example, typical present day (X, Y, Z) dimensions for free layer **10** are about (3 nm, 100 nm, 100 nm), and typical present day (X, Y, Z) dimensions for bias regions **12** and **14** are about (3-15 nm, 30 nm, 200 nm).

The ever-decreasing dimensions of free layer **10** and bias layers **12** and **14** have led to the appreciation of new problems in small bias layers which are either absent or not as apparent in larger structures. One such problem is statistical variability in performance due to crystal grain structure and orientation within bias layers **12** and **14**. This leads to variations of the magnetization direction of the individual grains comprising the bias layers **12** and **14**.

Figure 2 shows crystal grains **13a**, **13b**, **13c**, and **13d** within bias layer **12** of **Figure 1**, and also shows crystal grains **15a**, **15b**, **15c**, and **15d** within bias layer **14** of **Figure 1**. Crystal grains **13a-d** have corresponding magnetizations (Y-components) **18a-d**, and crystal grains **15a-d** have corresponding magnetizations (Y-components) **20a-d**. Magnetizations **18a-d** and **20a-d** typically vary from grain to grain, as indicated by the variable number of arrows within each crystal grain on **Figure 2**. More precisely, the variable number of arrows within each crystal grain of **Figure 2** schematically indicate the variable contribution of each grain to longitudinal magnetization **16** of free layer **10**. The contributions of the grains to magnetization **16** can vary due to a variable magnitude and/or direction of magnetization within the grains.

The main reason for variability of magnetizations **18a-d** and **20a-d** is that materials typically used for bias regions **12** and **14** are magnetically anisotropic and are typically deposited as polycrystalline films having grains with random orientations. For example, CoPt is easy to magnetize along the crystal c axis, and is more difficult to magnetize in other directions. The larger the angle between the magnetization direction and the crystal c axis,

the more difficult CoPt is to magnetize, since all basal plane directions (i.e., directions perpendicular to the c axis) are hard magnetization directions.

On **Figure 1**, the growth direction is the +X direction,
5 and materials are typically deposited as layers in the Y-Z plane. Bias layers **12** and **14** are typically formed by deposition techniques, such as sputter deposition or ion beam deposition which do not inherently provide perfect control over crystal grain orientation. Therefore, unless
10 further steps are taken, the grain orientation within bias layers **12** and **14** is entirely random. Methods for reducing the randomness of gain orientation are known, such as deposition of layers **12** and **14** on top of a suitable seed layer (such as Cr or a Cr containing alloy). However,
15 introduction of a seed layer typically does not completely remove the randomness of grain orientation, at least in the Y-Z plane (i.e., the growth plane). For example, in CoPt grown on top of Cr, the c axis of the CoPt grains is constrained to lie within the growth plane by the Cr seed
20 layer, but is random within this plane. This is achieved by lattice matching the atomic spacing of the seed layer to the atomic spacing of a plane including the c-axis of the hard bias layer material.

Thus, with or without the use of a seed layer, when
25 magnetizations **18a-d** and **20a-d** are set by the biasing magnetic field in this example, remanent magnetizations **18a-d** and **20a-d** vary depending on the angle between the crystal c axis of grains **13a-d** and **15a-d** and the direction of the biasing magnetic field (i.e., Y on **Figures 1** and **2**).

30 The variability of magnetizations **18a-d** and **20a-d** of **Figure 2** undesirably leads to variability in magnetization **16** in free layer **10**. As the number of grains contributing

to magnetization **16** decreases, the relative standard deviation (i.e., the standard deviation divided by the mean) of magnetization **16** increases, since an average is effectively being taken over the number of grains which
5 contribute to magnetization **16**. Typical grain sizes are no smaller than about 7-10 nm in lateral (i.e., Y-Z plane) extent, since grains which are smaller are known to have undesirably reduced stability. Thus the number of grains in bias layers **12** and **14** decreases as the physical size of
10 bias layers **12** and **14** decreases, thereby undesirably increasing the variability of magnetization **16** in free layer **10**.

Variability of magnetization **16** has undesirable consequences in manufacturing. To illustrate, let M_0 be
15 the minimum magnetization **16** required to force free layer **10** into a single domain state, and let M be the nominal design magnetization **16**. A population of manufactured devices will exhibit a distribution of values for magnetization **16**, centered on the nominal value M . If M is
20 chosen to be just above M_0 , then a significant fraction of the population will fail due to insufficient magnetization **16**. If M is chosen such that relatively few members of the population fail due to insufficient magnetization **16**, then many members of the population will have unnecessarily
25 reduced sensitivity due to magnetization **16** being substantially higher than is required.

Figure 3 shows another known configuration, as taught in US Patent 5,434,826, for biasing free layer **10** of a magnetic sensor. In the configuration of **Figure 3**, bias
30 layers **12a** and **12b** are separated by an interposing layer **24**, and bias layers **14a** and **14b** are also separated by an interposing layer **24**. Magnetizations **18a-b** and **20a-b** are

set within bias layers **12a-b** and **14a-b** respectively, and cooperatively provide magnetization **16** to free layer **10**.

SUMMARY

5 It is an object of the present invention to reduce the impact of magnetic bias variability on magnetic sensor performance. The present invention provides a magnetic sensor having two bias layers separated by a decoupling layer to eliminate exchange coupling between the bias
10 layers. In one embodiment of the invention, the two bias layers have differing coercivities, such that the biases provided by the bias layers to the free layer are independently adjustable. In another embodiment of the invention, the grain structures of the two bias layers are
15 substantially decorrelated by the decoupling layer.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a portion of a prior art magnetic sensor including a free layer and bias structures.

20 **Figure 2** shows typical crystal grain structure within a portion of a prior art magnetic sensor.

Figure 3 shows a prior art magnetic sensor having multilayer bias structures that cooperatively provide a bias to the free layer.

25 **Figure 4** shows a portion of a magnetic sensor having multilayer bias subassemblies that independently provide biases to the free layer, in accordance with an embodiment of the invention.

30 **Figure 5** shows crystal grain structure within a portion of a magnetic sensor in accordance with an embodiment of the invention.

Figures 6a-6c show measured hysteresis curves from a multi-layer hard bias structure for several different decoupling layer thicknesses.

5 DETAILED DESCRIPTION

Figure 4 shows a portion of a magnetic sensor having multilayer bias subassemblies that independently provide multiple biases to free layer **10**, in accordance with an embodiment of the invention. Bias layers **12a** and **12b** are
10 separated by a decoupling layer **26**. Similarly, bias layers **14a** and **14b** are separated by a decoupling layer **26**. Decoupling layers **26** function to substantially eliminate exchange coupling between layers **12a** and **12b** (and also between layers **14a** and **14b**). In addition, the coercivities
15 of layers **12a** and **12b** differ, as do the coercivities of layers **14a** and **14b**. Bias layers **12a** and **12b**, combined with decoupling layer **26**, make up a bias subassembly, as do layers **14a**, **14b**, and **26**. Magnetizations **18a** and **20a** provide a bias **16a** to free layer **10**, and magnetizations **18b**
20 and **20b** provide a bias **16b** to free layer **10**. Magnetization **16** is determined by the combined effect of biases **16a** and **16b**. Magnetizations **16**, **18a-b**, and **20a-b** are to be understood as Y-components of the magnetizations in the corresponding regions (i.e., **10**, **12a-b** and **14a-b**
25 respectively).

The different coercivities of bias layers **12a** and **12b** (as well as **14a** and **14b**), in combination with the decoupling provided by decoupling layers **26**, makes biases **16a** and **16b** independently adjustable. For example, suppose
30 the coercivity of layers **12a** and **14a** is H_{c1} and the coercivity of layers **12b** and **14b** is H_{c2} , where $H_{c2} > H_{c1}$. An applied bias magnetic field having a strength greater

than H_{c2} will alter the remanent magnetization of layers **12a-b** and **14a-b**, thus altering both biases **16a** and **16b**. An applied bias magnetic field having a strength less than H_{c2} but greater than H_{c1} will alter the remanent magnetization of layers **12a** and **14a** (thus altering bias **16a**), but will leave the remanent magnetization of layers **12b** and **14b** substantially unaltered (so bias **16b** is substantially unaltered). Here remanent magnetization is the magnetization remaining when the applied bias magnetic field is removed. Naturally, the independent adjustability of biases **16a** and **16b** seen in this example is also obtained if $H_{c2} < H_{c1}$.

In order to obtain independent adjustability of biases **16a** and **16b** in this manner, the minimal condition is that either magnetizations **18a** and **18b** are independent, or magnetizations **20a** and **20b** are independent. The embodiment of **Figure 4**, where both magnetizations **18a** and **18b** are independent and magnetizations **20a** and **20b** are independent is preferred because it provides improved adjustability of biases **16a** and **16b**.

In the embodiment of **Figure 4**, the primary function of decoupling layers **26** is to substantially eliminate exchange coupling between layers **12a** and **12b** (as well as between layers **14a** and **14b**). The reason for this is that layers **12a** and **12b** act substantially as a single magnetic body in the presence of exchange coupling between layers **12a** and **12b**. For example, magnetizations **18a** and **18b** may be constrained to be parallel or antiparallel by exchange coupling between layers **12a** and **12b**. Thus, elimination of such exchange coupling is required to obtain independent adjustability of biases **16a** and **16b**.

Suitable materials for decoupling layer **26** include:
Rhodium (Rh); fcc metals or alloys; bcc metals such as
Chromium (Cr), Tantalum (Ta), Molybdenum (Mo), Tungsten
(W), or Niobium (Nb); and CrX alloys where X is Molybdenum
5 (Mo), Manganese (Mn), Cobalt (Co), Titanium (Ti), Tantalum
(Ta), Vanadium (V), Zirconium (Zr), or Niobium (Nb).

Exchange coupling generally tends to decrease as the
thickness of decoupling layer **26** increases. Methods for
suppressing exchange coupling typically involve use of
10 materials at magnetic interfaces having electronic band
structures that do not sustain the presence of a magnetic
spin. Therefore, the localized magnetic moments at these
interfaces are suppressed, thereby suppressing exchange
coupling.

15 Exchange coupling is a physical phenomenon that is
different from magnetostatic interaction. Magnetostatic
interaction is the ordinary magnetic interaction between
magnetizations **18a** and **18b** (and also between magnetization
20a and **20b**). Magnetostatic interaction is typically not a
20 strong enough effect to force layers **12a** and **12b** (or layers
14a and **14b**) to act substantially as a single magnetic
body. Therefore, it is unnecessary for decoupling layers
26 to substantially reduce or eliminate magnetostatic
interaction.

25 Suitable materials for bias layers **12a-b** and **14a-b**
include binary, ternary and quaternary alloys of Co.
Binary alloys $\text{Co}_x\text{Pt}_{1-x}$ where $0.5 < x < 1$ are suitable. CoPt
alloys over this composition range exhibit large saturation
magnetization values and the magnetocrystalline anisotropy
30 achieves a maximum for compositions with x in a range of
about 0.7 to 0.8. Thus, $\text{Co}_{0.75}\text{Pt}_{0.25}$ alloys are very
attractive for producing ultra thin hard bias layers with

high remanent magnetization and high bias ratios
(magnetization ratio between the hard bias and the free
sensor layers). Rhodium is a suitable spacer layer for
suppressing exchange coupling between $\text{Co}_{0.75}\text{Pt}_{0.25}$ layers. In
5 practice, layers **12a-b**, **14a-b**, **10** and **26** are typically
grown within a material growth/deposition system employing
ion beam deposition or sputtering techniques. As is known
in the art, the material properties of these layers is
significantly affected by the growth methodology and
10 therefore to achieve optimum device functionality, the
growth of the materials of choice must be optimized in the
particular tool employed.

Preferably, decoupling layers **26** act as seed layers
that tend to cause the grains within layers **12a** to have
15 their easy magnetization directions parallel to the
interface between layers **12a** and **26** (and similarly for
layer **14a**). This can be done by lattice matching the
atomic spacing of decoupling layer **26** to the atomic spacing
of a plane including the c-axis of the material of layer
20 **12a** (and of layer **14a**).

The independently adjustable biases **16a** and **16b**
provided by the embodiment of **Figure 4** advantageously
address the problem of crystal grain induced magnetization
variability discussed above. Recall that the net effect of
25 magnetization variability is to oblige a designer to choose
between a relatively high design magnetization **16** (thereby
reducing sensitivity and improving yield) and a relatively
low design magnetization **16** (thereby improving sensitivity
and reducing yield).

30 For example, suppose layers **12a** and **14a** have
coercivity H_{c1} , and that layers **12b** and **14b** have coercivity
 $H_{c2} > H_{c1}$. A designer could select a relatively low design

magnetization **16**, provided only by bias **16a** from magnetizations **18a** and **20a**. Magnetizations **18a** and **20a** can be set without substantially altering magnetizations **18b** and **20b** by application of a bias magnetic field having a strength H_1 between H_{c1} and H_{c2} . Since magnetizations **18b** and **20b** are typically negligible in the as-grown material, and are not altered by this applied bias field, magnetization **16** in free layer **10** is provided only by bias **16a**. If magnetizations **18b** and **20** are not negligible in as-grown layers **12b** and **14b**, then these layers can be demagnetized using known methods to render magnetizations **18b** and **20b** negligible.

A sensor containing this bias structure can be subjected to a pass/fail test to determine if magnetization **16** provided only by bias **16a** is sufficiently large to force free layer **10** into a single domain state. For example, one suitable test is measurement of sensor resistance as a slowly varying magnetic field is applied to the disk-facing surface of the sensor. A satisfactory sensor will have a resistance vs. field curve which is continuous and has a continuous derivative, and which exhibits minimal hysteresis over several cycles of the magnetic field. Sensors which pass the test need no further processing. Sensors which fail the test can be subjected for a second time to a biasing magnetic field, where the strength of the biasing field is increased to a value H_2 which is greater than H_{c2} . Such a magnetic field will alter magnetizations **18b** and **20b**, and after removal of the biasing magnetic field, magnetizations **18b** and **20b** will provide bias **16b** to free layer **10**. In this case, biases **16a** and **16b** both contribute to magnetization **16** in free layer **10**.

In many cases, the increased magnetization **16** provided by biases **16a** and **16b** together (compared to the magnetization provided by bias **16a** alone) will suffice to force free layer **10** into a single domain state, thus
5 resulting in a useful sensor. Pass/fail testing as described above is also suitable for making the determination of whether or not the sensor is useful. The net effect of this method is to obtain increased sensor sensitivity (in the fraction of the sensor population which
10 passes the first round of testing) with a reduced yield penalty (since some fraction of the devices which fail the first round of testing are rendered useful by the increased magnetic bias). Of course, the method would work just as well for $H_{c1} < H_{c2}$, and the above description is directly
15 applicable with a and b interchanged.

Although the above method is described in application to a single device, it can also be applied to multiple devices. For example, testing can be done either at the single slider level, or at the row level (where a row
20 contains multiple sliders). Row level testing would typically make use of known statistical sampling techniques to realize the above advantages of increased sensitivity and increased yield while minimizing testing.

Other variations of the above method are possible.
25 For example, biasing magnetic fields having strengths H_1 and H_2 as indicated above would typically be applied in the Y direction on **Figure 4**, to maximize the resulting longitudinal magnetization **16**. However, it is also possible to apply biasing magnetic fields having strengths
30 H_1 and/or H_2 in directions other than the longitudinal direction (i.e. the direction of electric current flow). In this manner, magnetization **16** can be varied by varying

biases **16a** and/or **16b** over a continuous range, thereby providing greater flexibility.

Figure 5 shows crystal grain structure within a portion of a magnetic sensor in accordance with an embodiment of the invention. In the configuration of **Figure 5**, crystal grains **13a-d** (corresponding to layer **12a** on **Figure 4**) have magnetizations (Y-components) **18a-d** respectively, and crystal grains **13e-h** (corresponding to layer **12b** on **Figure 4**) have magnetizations (Y-components) **18e-h** respectively. Similarly, crystal grains **15a-d** (corresponding to layer **14a** on **Figure 4**) have magnetizations (Y-components) **20a-d** respectively, and crystal grains **15e-h** (corresponding to layer **14b** on **Figure 4**) have magnetizations (Y-components) **20e-h** respectively. Magnetizations **18a-h** and **20a-h** are shown on **Figure 5** with a variable number of arrows to indicate the variability of these magnetizations as discussed in connection with **Figure 2**. Magnetizations **18a-h** and **20a-h** provide magnetization **16** in free layer **10**.

Crystal grains **13a-d** are separated from crystal grains **13e-h** by decoupling layer **26**. Likewise, crystal grains **15a-d** are separated from crystal grains **15e-h** by decoupling layer **26**. In the embodiment of **Figure 5**, decoupling layer **26** is deposited on top of grains **13e-h** and then grains **13a-d** are deposited on top of decoupling layer **26**. Similarly, decoupling layer **26** is deposited on top of grains **15e-h** and then grains **15a-d** are deposited on top of decoupling layer **26**. One function of decoupling layer **26** is to ensure that grains **13a-d** are substantially uncorrelated with grains **13e-h** (and that grains **15a-d** are substantially uncorrelated with grains **15e-h**). In the absence of decoupling layers **26**, crystal grains as shown in **Figure 2** would form, since

crystal grain growth is typically columnar in the growth direction (X direction on **Figures 2 and 5**). Decoupling layer **26** also substantially eliminates exchange coupling between grains **13a-d** and grains **13e-h** (and also between
5 grains **15a-d** and grains **15e-h**).

The configuration of **Figure 5** therefore increases the number of statistically independent grains which contribute to magnetization **16** in free layer **10**. As indicated above, this increased number of grains advantageously reduces the
10 variability of magnetization **16**. In order to realize the advantages of the embodiment of **Figure 5**, it is not necessary for the coercivity of grains **13a-d** to differ from the coercivity of grains **13e-h**. Differing coercivities are also not required between grains **15a-d** and **15e-h**. Suitable
15 materials for grains **13a-h** and **15a-h** and decoupling layer **26** on **Figure 5** are as indicated above in connection with **Figure 4**.

Figures 6a-c show measured hysteresis curves from a multi-layer hard bias structure for several different
20 decoupling layer thicknesses. The results of **Figures 6a-c** are obtained from structures where bias layers (**12a, 12b, 14a, 14b**) are 5 nm thick layers of Co₃Pt (i.e., Co_{0.75}Pt_{0.25}), and decoupling layer **26** is Rh. The thickness of decoupling layer **26** is 0.3 nm, 1 nm and 8 nm in the examples of
25 **Figures 6a, 6b, and 6c** respectively. As indicated on the titles of the plots in **Figures 6a-c**, the overall layer sequence in these experiments is seed layer (~ 11 nm of CrMo), first bias layer (Co₃Pt), decoupling layer (Rh), second bias layer (Co₃Pt), and Ta layer.

30 **Figure 6a**, with a 0.3 nm thick decoupling layer, shows a hysteresis curve that is typical for a single magnetic body, which shows that the two bias layers are strongly

exchange coupled. **Figure 6c**, with an 8 nm thick decoupling layer, shows a hysteresis curve that is not typical for a single magnetic body. Instead, the structure acts as two independent magnetic bodies, which indicates substantial elimination of exchange coupling. The hysteresis curve shown on Fig. 6c shows that magnetization reversal occurs in two distinct steps, at applied fields of roughly 1 kOe and 2 kOe, which correspond to magnetization reversal in the second and first bias layers respectively. Thus the two bias layers of **Figure 6c** have differing coercivities, even though the material composition of the two bias layers is the same. The explanation for these differing coercivities is that the coercivity of a thin layer depends in part on the crystallographic properties (e.g., symmetry, grain size and/or crystal orientation) and thickness of the layer that it is grown upon. The two bias layers in the example of **Figure 6c** are grown on different materials belonging to different crystallographic groups (i.e., CrMo is bcc, and Rh is fcc) and having different thicknesses (i.e., CrMo seed thickness is ~ 11 nm and Rh decoupling layer thickness is 0.3 nm). **Figure 6b**, with a 1 nm thick decoupling layer, shows behavior intermediate to that of **Figures 6a** and **6c**.

Thus the condition of differing coercivities of bias layers **12a** and **12b** (and of **14a** and **14b**) relating to the embodiment of **Figure 4** can be obtained even if layers **12a** and **12b** (and/or layers **14a** and **14b**) have the same material composition.

The invention has now been described in accordance with several exemplary embodiments, which are illustrative, rather than restrictive. Thus, the invention is capable of many variations in detailed implementation, which may be

derived from the description contained herein by a person of ordinary skill in the art. For example, the above embodiments relate to decoupling of two bias layers, but three or more bias layers can also be decoupled according
5 to the invention.